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Irregular effects on the transition from regular to Mach reflection of shock waves in wind tunnel flows

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Configurations of shock wave reflection in steady supersonic flows have been experimentally investigated using a combination of two wedges. It has been experimentally proved by a symmetric arrangement that both regular and Mach reflections are possible in the dual-solution domain for various aspect ratio models. In the arrangement for the purpose of clarifying the influence of the wedge three-dimensionality, the transition from regular to Mach reflection can happen at any inlet aspect ratio, both when the inlet aspect ratio is increased and when it is reduced. The inlet aspect ratio has no effect on the transition provided it is high enough for the regular reflection point at the spanwise centre to be free from information from wedge edges. Flow visualization data produced using the vapour screen technique indicate that, in a region influenced by information from wedge edges, the three-dimensionality of experimental models promotes regular reflection rather than Mach reflection. To study the criteria for the transition between regular and Mach reflections, an asymmetric arrangement of two wedges has been used, and a hysteresis effect is clearly evident. The transition from regular to Mach reflection, however, occurs significantly below the detachment condition, and moreover, the repeatability of the transition angle is not satisfactorily achieved. These experimental results imply that wind tunnel disturbances may dominate the transition in the dual-solution domain. The stability of regular reflection in the dual-solution domain is discussed, and effects of free-stream disturbances are experimentally examined by producing water vapour in the free stream as an artificial disturbance.

1. Introduction

At a sufficiently high Mach number in steady flow, three-shock theory permits both regular and Mach (see figure 1) reflections in the so-called dual-solution domain of incident shock wave angles. Understanding the mechanism of the transition from one reflection configuration to the other is essential for the design of supersonic vehicles. Hornung, Oertel & Sandeman (1979) predicted that a hysteresis of the transition between the two reflections would occur if the shock wave angle β were adjusted during the flow. Hornung & Robinson (1982) then investigated the hysteresis effect experimentally. It was found, however, that the transition occurred at the von Neumann condition regardless of the direction of β change, and thus the accuracy of this prediction could not be confirmed.

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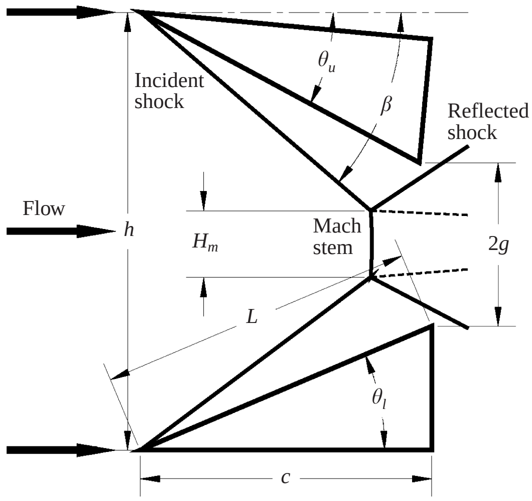

FIGURE 1. Mach reflection configuration in an asymmetric arrangement and nomenclature: c, wedge chord length; g, half of the gap between wedge trailing edges; h, distance between wedge leading edges; H_m, Mach stem length; L, wedge length on the oblique side; β, angle of incident shock wave; θ_l, lower deflection angle; θ_u, upper deflection angle.

Recently, several two-dimensional numerical works (for example, Ivanov *et al.* 1998*c*) have demonstrated hysteresis effects, and differences between the numerical and experimental results have been reconsidered. One cause of the differences is the three-dimensional effects of wind tunnel models. In experiments by Chpoun *et al.* (1995), both regular and Mach reflections were observed in the dual-solution domain, and the existence of the hysteresis effect appeared to be proved. However, extensive and careful experiments by Fomin *et al.* (1996) showed that the effect observed in the experiments by Chpoun *et al.* (1995) was a consequence of the strong three-dimensionality of the setup used. Skews (1997) then analysed transverse wave patterns and flow fields around three-dimensional experimental models and determined the minimum inlet aspect ratio (the ratio of wedge width w to h) to avoid edge influences. The analysis showed that transverse perturbations due to edge effects triggered the transition from regular to Mach reflection, and led to an assumption that the Mach stem length decreased monotonically from the periphery toward the spanwise centre. Three-dimensional computations performed by Ivanov *et al.* (1998*a*) at the same time, however, showed non-monotonical variation in Mach stem length in the spanwise direction and also demonstrated a situation in which a regular reflection exists between Mach reflections in the vicinity of the spanwise centre and on the periphery. Sudani *et al.* (1999*b*) and Ivanov *et al.* (1999) then applied the vapour-screen technique to provide an image of the three-dimensional structure of the Mach reflection configuration, and showed good agreement with the computations of Ivanov *et al.* (1998*a*). These results emphasize the need to reconsider the effects of edge information on the shock reflection configuration in the spanwise centre because the effects are unavoidable in experimental situations.

In the first series of tests (presented in Sudani *et al.* 1999*b*), a symmetric arrangement, in which one wedge is fixed and the other changes its vertical location continuously, was attempted. The resulting data seemed to indicate some effects of inlet aspect ratio on the transition from regular to Mach reflection, but also were significantly different from results of unsteady three-dimensional computations performed by Mizobuchi, Sato & Sudani (1999). In these computations, the transition never occurs in the symmetric arrangement unless the reflected shock impinges on the trailing edge of the wedge. In this paper, the results obtained in the first series of tests are first presented. Effects of inlet aspect ratio on the transition from regular to Mach reflection are then discussed using further experimental data. The influence of wedge three-dimensionality on reflection configurations is also demonstrated using vapour-screen visualization data.

To reconsider the criteria for the transition between regular and Mach reflections when the deflection angle (i.e. the incident shock angle) is varied continuously, an asymmetric arrangement, in which one wedge changes its deflection angle while the other does not, was used. Because of limitations of blockage ratio, a model support must be designed as simply as possible, and therefore the asymmetric arrangement was selected. Sudani & Hornung (1998) suggested that there should be a dual-solution domain in the asymmetric arrangement as well as the conventional symmetric one. Li, Chpoun & Ben-Dor (1999) independently investigated configurations of asymmetric shock wave reflection both analytically and experimentally, and demonstrated a dual-solution domain between two criteria analogous to the well-known detachment and von Neumann criteria. Angles of the transition from regular to Mach reflection and vice versa also demonstrated good agreement between the analysis and results of experiments. In the first series of tests by Sudani *et al.* (1999*b*), a hysteresis effect was clearly observed in the asymmetric arrangement, but the transition from regular to Mach reflection occurred significantly below the detachment condition. Mizobuchi *et al.* (1999) then performed unsteady three-dimensional computations of the asymmetric cases and showed that the transition occurred close to the detachment condition, in contrast to the experimental data. To clarify factors in the different results, the transition angle, especially from regular to Mach reflection in the asymmetric arrangement, has been investigated in several series of tests, and the repeatability of the transition angle is discussed in this paper.

Another major cause of the differences between numerical and experimental results concerning the existence of the hysteresis effect predicted by Hornung *et al.* (1979) is thought to be free-stream disturbances, which exist only in wind tunnel experiments. Ivanov *et al.* (1996) first investigated numerically the stability of both regular and Mach reflection configurations by adding flow perturbations in the vicinity of the reflection point or in the free stream, and showed that regular reflection was less stable than Mach reflection in the dual-solution domain. A physical argument on such stability considerations was provided by Hornung (1997). This work was then extended by Sudani & Hornung (1998), together with a numerical study to test Hornung's (1997) discussion. Ivanov *et al.* (1998*b*) also argued that wind tunnel disturbances had an effect on results, using data obtained from experiments conducted in different types of wind tunnel. The results of the experiments indicated that the range of incident shock angle where both regular and Mach reflections were observed was wider in a free-jet test section than in a rectangular one. In this paper, the hysteresis phenomenon and transition criteria in a disturbed situation have been experimentally studied using water vapour as an artificial disturbance. Effects of disturbances, which Sudani *et al.* (1999*a*) identified as the dominant cause of the transition to Mach reflection in the dual-solution domain, are also discussed with relation to the repeatability of the transition angle.

M_∞	p_0 (MPa)	T_0 (K)	Re (m^{-1})
3.003	0.52	280	4.2×10^7
3.511	0.80	280	5.0×10^7
4.015	1.29	280	6.4×10^7

TABLE 1. Experimental conditions. M_∞, free-stream Mach number; p_0, stagnation pressure; T_0, stagnation temperature; Re, unit Reynolds number.

2. Experimental setup

2.1. *Facility and experimental conditions*

Experiments were conducted in a supersonic wind tunnel at the National Aerospace Laboratory of Japan (NAL). This is a blowdown-type wind tunnel with a closed test section of 1 m × 1 m. The free-stream Mach number can be varied from 1.4 to 4 using a flexible nozzle. A control valve maintains constant pressure in the settling chamber to produce uniform flow for approximately 35 s irrespective of free-stream Mach number.

Experimental conditions in these studies are tabulated in table 1. A higher Mach number is preferable to make it easier to distinguish between the von Neumann and detachment criteria. Accordingly, Mach numbers of 3, 3.5 and 4 were chosen, and measured values are also provided in the table. Variations in Mach number and static pressure from run to run during each series of tests were within ± 0.001 and ± 0.01 kPa, respectively. The pressure fluctuation of the free stream $\sqrt{\overline{(\Delta p_s)^2}}/q_\infty$, where Δp_s is the difference between the static pressure and the mean value and q_∞ is the dynamic pressure of the free stream, is approximately 1.5% although the data were acquired at lower Mach numbers ($M_\infty \leqslant 2$) than used here. (See Hashidate *et al.* 1982 for details.) The analysis of static pressure fluctuation demonstrated that the power spectra had the same trend in any period during a run. It also showed that there was no noticeable turbulence with a low frequency (less than 2–3 Hz).

2.2. *Experimental models and model arrangements*

An arrangement of two wedges is normally used in this kind of experiment to avoid viscous boundary-layer effects on a reflecting wall. In these studies, while the lower wedge was fixed, the position of the upper wedge was altered during each run in the following two ways:

(i) Symmetric arrangement. The upper wedge is moved vertically without changing its deflection angle θ_u (figure 2*a*). When the wind tunnel operation starts, the wedges must be located away from each other so that a supersonic flow can be established between the wedges without choking. After a uniform flow has been established, the upper wedge is moved toward the lower wedge and then back to the initial position.

(ii) Asymmetric arrangement. The deflection angle of the upper wedge is varied continuously (figure 2*b*). Note that the pivot for the model sting moves along a vertical straight line. This causes slight movement of the leading edge in both vertical and horizontal directions when the angle of attack of the sting is altered. The streamwise positions of the leading edges of the upper and lower wedges are arranged so as to be the same as when the configuration is symmetrical. In this configuration, the ratio of g to L is designed to be 0.37 (identical to that in Hornung & Robinson 1982). For each model, the position of the lower wedge is determined in such a way that g/L remains constant. The angle of attack of the upper wedge must start with a

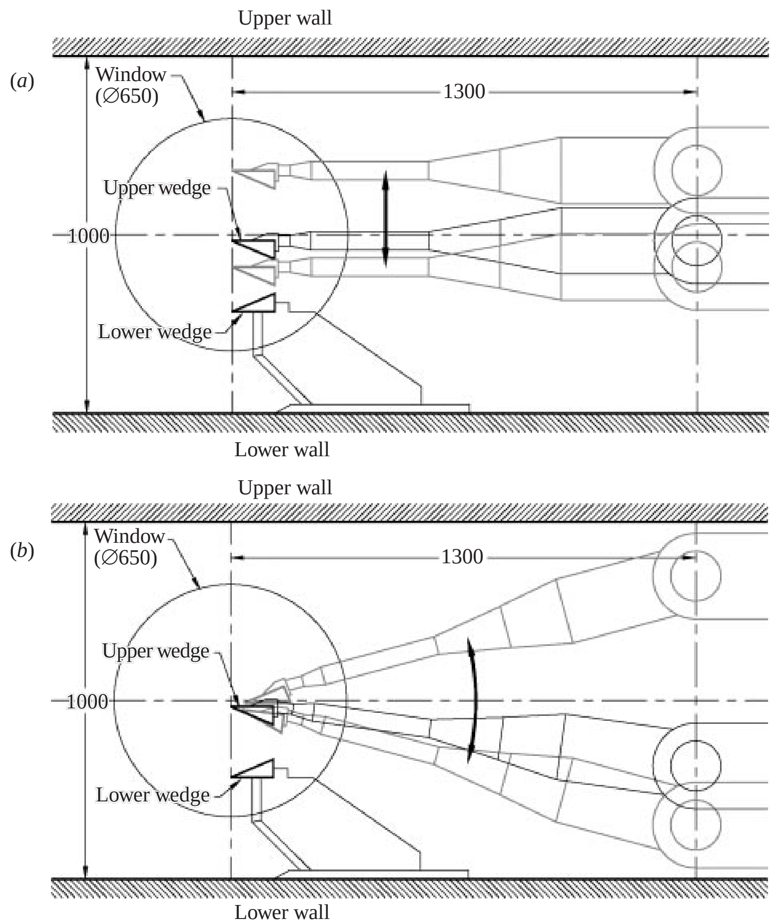

FIGURE 2. Schematic of model arrangements in the test section. (*a*) Symmetric arrangement in which the upper wedge is moved vertically without changing its deflection angle. (*b*) Asymmetric arrangement in which the deflection angle of the upper wedge is varied continuously. Dimensions in mm.

considerable negative value to avoid choking. The angle of attack is first increased until a Mach reflection takes place, and then reduced back to the initial value.

Experimental models used in these studies are listed in table 2. The size of the wedges was chiefly limited by the blockage ratio for the tunnel start and by the strength of the wedge support, especially before a uniform flow was established. The wedge aspect ratios (w/L) for models 3 and 5 were set to be greater than the maximum presented in Fomin *et al.* (1996) for the purpose of achieving more two-dimensional flows. The wedges are located a sufficient distance away from the top and bottom wind tunnel walls. The widths (spans) of the wedges are also small in relation to the tunnel width. The flow field generated by the wedges should therefore be free from the influence of tunnel wall boundary layers. Deflection angles were measured when the wedges were mounted in the test section. Values for the upper and lower wedges are also given in table 2, together with the designed angles θ_{design} chosen from the dual-solution domain. A discrepancy between the designed and measured values caused a slightly asymmetric flow in the sym-

Model	M_∞	c (mm)	w (mm)	w/L	θ_{design} (deg.)	θ_u (deg.)	θ_l (deg.)
1	4.015, 3.511	120	330	2.53	23.0	22.9	22.6
2	4.015, 3.511	80	330	3.80	23.0	22.9	22.6
3	4.015, 3.511	80	480	5.52	23.0	22.9	22.6
4	3.003	120	330	2.58	20.5	20.5	20.2
5	3.003	80	480	5.62	20.5	20.5	20.2

TABLE 2. Experimental models. M_∞, free-stream Mach number; w, wedge width; θ_u and θ_l, measured values in the symmetric arrangement; θ_{design}, designed deflection angle in the symmetric arrangement.

metric arrangement. This slight discrepancy, however, has no significant influence on the arguments put forward in this paper because the flow deflection or velocity difference in a shear layer generated behind a regular-reflection point is negligibly small.

2.3. *Flow visualization techniques*

Colour schlieren images were obtained using a CCD camera and videotaped in the first series of tests, and a 3-CCD camera and a laserdisc recorder were used for all subsequent tests. All the schlieren images in this paper were captured from the videotapes or laserdiscs. In the symmetric arrangement, the frame-to-frame variation in upper wedge location was approximately 0.83 mm at a main wedge speed of 25 mm s^{-1}. In the asymmetric arrangement, the frame-to-frame variation in θ_u was approximately 0.067° at a main rate of change of 2° s^{-1}. The time from the tunnel start was superimposed on the video footage. The vertical location or angle of attack of the upper wedge was detected by the time recorded and the value measured with a potentiometer. The accuracy of the detection is estimated to be ± 0.5 mm and $\pm 0.05°$ for the symmetric and the asymmetric arrangement, respectively.

In the setup for the vapour-screen visualization, a solid-state 532-nm cw laser was used as a light source. The power was adjusted to approximately 1 W in a series of tests. The beam through an optical fibre was expanded to a light sheet of approximately 3 mm thickness using a combination of cylindrical lenses. Water was injected into the settling chamber through 30 holes (each 1 mm in diameter) after a uniform flow had been established. The amount of water injected was estimated at 150 g s^{-1}, while the mass flow rate of the free stream was approximately 300 kg s^{-1}. Because the water injected was carried to the nozzle entrance through four woven wire mesh screens (of wire diameter 0.508 mm and opening 1.306 mm), the air produced had sufficient moisture and was expanded through the supersonic nozzle while the moisture was condensing to form a fog. The water injection was, however, carried out in the vicinity of the tunnel axis, so that the fog seemed to be somewhat denser there than on the periphery. The water injection system needs to be improved to obtain more detailed images in future studies. The laser light sheet was shone into the test section at a perpendicular angle to the free-stream direction. Images were obtained from an oblique angle using a 3-CCD camera mounted outside the test section. A Mach number of 3 was selected for these studies because of some problems with injecting water under high pressure for higher Mach numbers.

3. Results and discussion

3.1. *Three-dimensional effects*

To confirm that both regular and Mach reflections are experimentally possible and to investigate effects of inlet aspect ratio (three-dimensionality) on the transition from regular to Mach reflection, the symmetric arrangement was used in which the inlet aspect ratio can be varied continuously. A sequence of schlieren pictures obtained in the first series of tests is shown in figure 3. Each wedge has a deflection angle in the dual-solution domain. The upper wedge first moves toward the lower wedge (figure 3*a* to *c*) and then moves away (figure 3*d* to *f*). Upper wedge locations in (*a*), (*b*), and (*c*) coincide with those in (*f*), (*e*), and (*d*), respectively. A regular reflection occurs initially (figure 3*a*) and persists until the inlet aspect ratio w/h is equal to 1.41 (figure 3*b*). Obviously, the regular reflection point at the spanwise centre shown in figure 3(*b*) is free from the influence of expansion fans emanating from the wedge trailing edges. Moreover, an inlet aspect ratio of 1.41 means that the regular reflection point at the spanwise centre is unaffected by signals from the corners of the wedge leading edge. The picture clearly demonstrates that a stable regular reflection can exist in the dual-solution domain. As the upper wedge moves away from the lower wedge, the Mach stem decreases its length. The Mach reflection then persists (figure 3*e*) even in the configuration in which the regular reflection was observed, and a hysteresis effect is confirmed. Although the hysteresis effect is different from that predicted by Hornung *et al.* (1979), the fact that both regular and Mach reflections are observed in the same wedge arrangement suggests the existence of the predicted hysteresis. The Mach reflection persists even when the distance between the two wedges increases further (figure 3*f*). The expansion fans affect the triple points of the Mach reflection configuration. The effect, however, is not sufficient for the Mach stem to be swallowed up downstream.

When the upper wedge is moved vertically toward the lower wedge without changing θ_u, the flow downstream of the regular-reflection point remains supersonic except for a condition very close to the detachment condition. No information downstream can therefore reach the reflection point to cause the transition to Mach reflection. If the transition were dominated by the three-dimensionality, i.e. if disturbances due to the edge effects influenced the regular reflection point transversely as explained by Skews (1997), the transition would occur without fail at a particular inlet aspect ratio irrespective of wedge aspect ratio w/c (or w/L). However, results obtained in the first series of tests using different (higher) aspect ratio wedges indicated that the transition to Mach reflection took place at an inlet aspect ratio significantly different from the one in figure 3 (Sudani *et al.* 1999*b*). Unsteady numerical simulations also demonstrated that, once a steady solution is obtained for uniform initial conditions, no subsonic flow was produced in the vicinity of reflection points of the incident shock wave, and that Mach reflection never occurred in the symmetric arrangement (Mizobuchi *et al.* 1999). Furthermore, if the hypothesis were correct, the transition phenomenon should be observed at the same inlet aspect ratio when experiments are repeated. Figure 4 shows time histories of wedge vertical position (together with the information on inlet aspect ratio) during a run for some cases with different motions of the upper wedge. In the cases indicated by a dash-dotted line and a dashed line in figure 4(*a*), the transition to Mach reflection (represented by a thick line) occurs at completely different positions, i.e. different inlet aspect ratios. In the other case (a solid line), the upper wedge is moved up and down twice during a run, but no transition is observed. Under another test condition (figure 4*b*), the transition to Mach

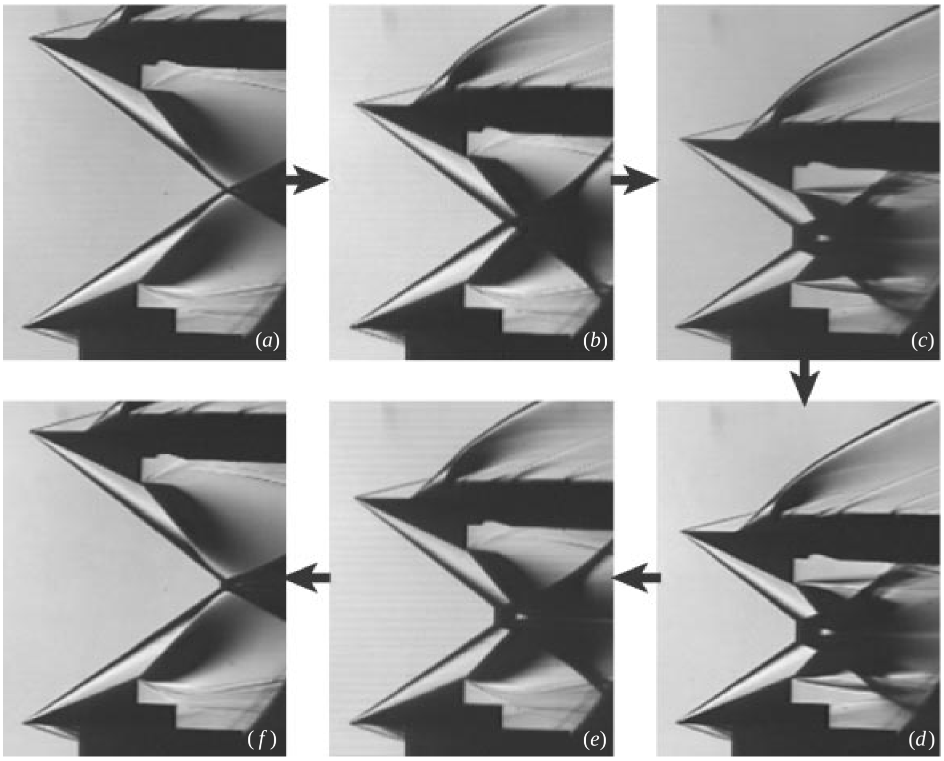

FIGURE 3. A sequence of schlieren pictures at the transition between regular and Mach reflections in the symmetric arrangement. Model 1, $M_\infty = 4.015$, $\theta_u = 22.9°$, and $\theta_l = 22.6°$. $w/h =$ (*a*) 1.09, (*b*) 1.41, (*c*) 1.68, (*d*) 1.68, (*e*) 1.41, and (*f*) 1.09.

reflection occurs when the upper wedge is moved away from the lower wedge, and in the second movement only. It is possible for the transition to Mach reflection to happen at any inlet aspect ratio both when the inlet aspect ratio is increased and reduced.

As mentioned in § 2.1, the repeatability of the free-stream Mach number is not a significant factor in the irregular phenomena. It was also confirmed that the time histories of free-stream static pressure and Mach number showed no significant change at the point of the transition, as shown in figure 4(*c*). The results for the symmetric cases suggest that the inlet aspect ratio, i.e. the three-dimensionality, has no effect on the transition to Mach reflection at the spanwise centre provided the inlet aspect ratio is high enough for the regular reflection point at the spanwise centre to be free from the edge information. No experimental results have been obtained to support the hypothesis that, for such a high inlet aspect ratio case, the three-dimensionality influences the regular reflection point transversely and causes the transition to Mach reflection. The transition is found to be caused by another factor than the three-dimensionality from the fact that the transition does not necessarily occur (as demonstrated in the case of the solid line in figure 4*a* or in the first movement of figure 4*b*). Since the transition occurs irregularly, the result also suggests the possibility that some disturbances existing in the free stream trigger the transition from a less stable regular reflection to a more stable Mach reflection in the dual-solution domain. The stability of reflection configurations and effects of free-stream disturbances are discussed in §§ 3.3 and 3.4.

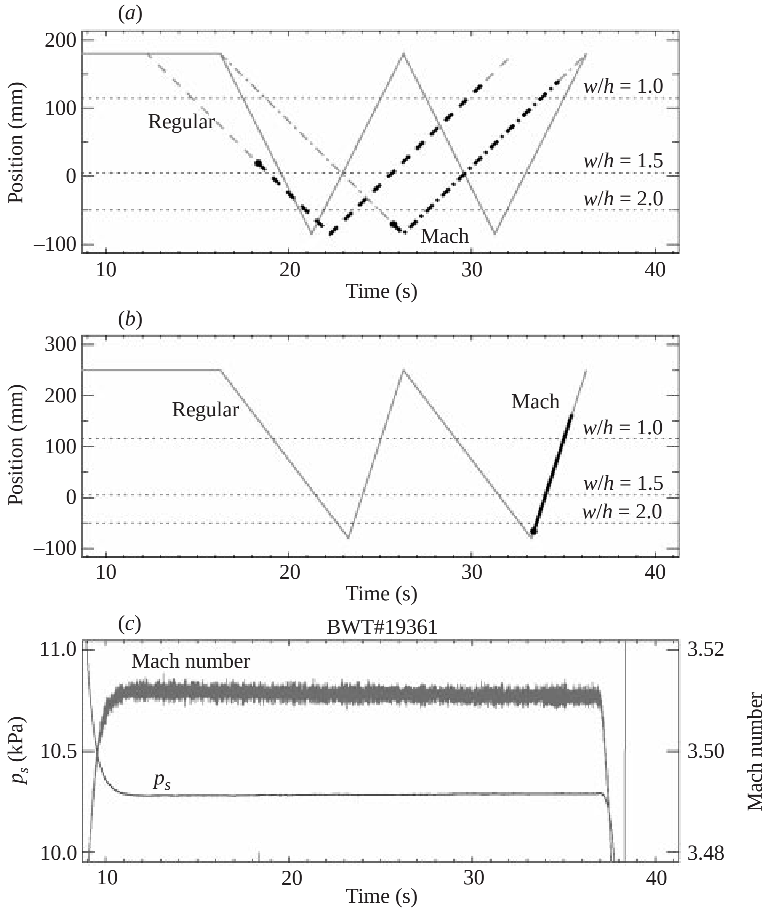

FIGURE 4. Time histories of the upper wedge position and the transition points between regular and Mach reflections. Thick lines, Mach reflection; thin lines, regular reflection; ●, transition from regular to Mach reflection. (*a*) $M_\infty = 4.015$, $\theta_u = 22.9°$, and $\theta_l = 22.6°$; (*b*) $M_\infty = 3.511$, $\theta_u = 22.9°$, and $\theta_l = 22.6°$. (*c*) Time histories of free-stream Mach number and static pressure p_s for case (*b*).

The question arises here as to how the three-dimensionality influences the configurations of shock wave reflection for a low inlet aspect ratio or on the periphery even for a high aspect ratio. The vapour-screen method was first applied by Sudani *et al.* (1999*b*) to visualize the three-dimensional structure of the Mach reflection configuration. Techniques for recording images have improved to allow finer resolution in these studies, so that the behaviour of reflection configurations at the transition becomes clearly visible. A typical example of vapour-screen images is shown in figure 5, together with a schlieren picture indicating the location of the laser light sheet. An image in the shape of a mouth is observed between the wedges. In the subsonic flow region behind the Mach stem, water droplets are vapourized because of the temperature rise, and the region is visible as a dark area, which is observed in the middle of the ‘mouth’. In the white regions around the dark region, the density of water droplets is increased by the incident and reflected shocks, but the temperature there is not so high as to vapourize the water droplets. The outer boundary of the white regions therefore corresponds to the reflected shocks, and the boundary of the black region represents the shear layers downstream of the triple points. The dark

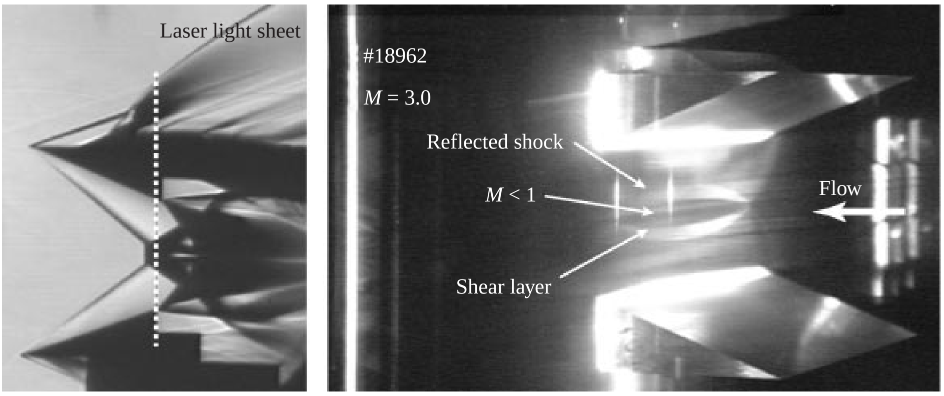

FIGURE 5. Vapour-screen and schlieren pictures in the asymmetric arrangement. Model 4, $M_\infty = 3.0$, $\theta_u = 21.0°$, and $\theta_l = 20.2°$.

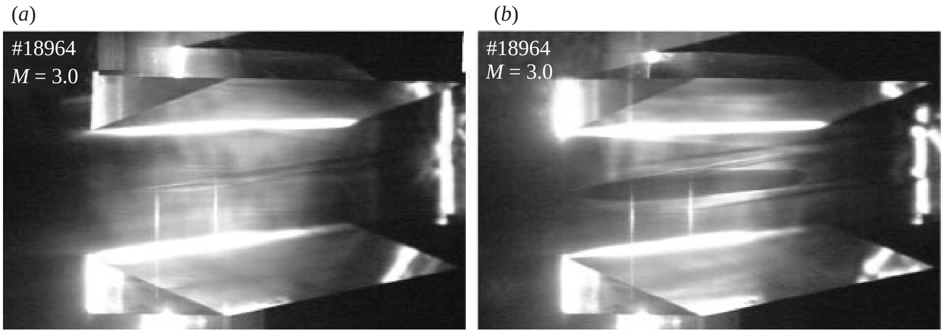

FIGURE 6. Vapour-screen pictures in the asymmetric arrangement for a high aspect ratio model. Model 5, $M_\infty = 3.0$, and $\theta_l = 20.2°$. $\theta_u =$ (*a*) 19.4° and (*b*) 21.0°.

region is observed to be of maximum width at the spanwise centre and diminish near the side ends.

Figure 6 shows vapour-screen images for a higher aspect ratio model in the asymmetric arrangement. In figure 6(*a*), a Mach stem is observed only near the spanwise centre, and regular reflections occur on both sides of the Mach reflection. The coexistence of regular and Mach reflections in the spanwise direction as already demonstrated by three-dimensional computations (Ivanov *et al.* 1998*a* and Mizobuchi *et al.* 1999) is therefore proved experimentally. The figure also indicates that the periphery Mach reflection by edge effects is still far downstream and is not significant in terms of the occurrence of Mach reflection at the spanwise centre. These visualization data imply that three-dimensional effects of wedges promote regular reflection rather than Mach reflection, and that a low aspect ratio has the potential to keep regular reflection beyond the detachment condition, i.e. where regular reflection is impossible for ideal two-dimensional flow.

3.2. *Transition criteria*

To investigate the criteria for the transition from regular to Mach reflection and vice versa, the asymmetric arrangement of the two wedges has been used. Even in this arrangement, criteria corresponding to the von Neumann and detachment conditions exist as shown in figure 7. The thick solid curve originating from θ_t represents the reflected shock locus at one of the transition (from regular to Mach reflection)

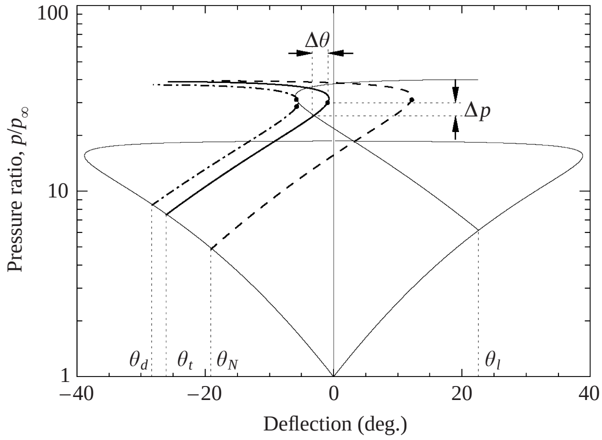

FIGURE 7. Shock polars in asymmetric cases for $M_\infty = 4.015$. Thick solid line originating from θ_t, reflected shock locus at the transition to Mach reflection; dashed line from θ_N, reflected shock locus in the von Neumann condition; dash-dotted line from θ_d, reflected shock locus in the detachment condition. Deviations of Δp and $\Delta\theta$ denote necessary variations in static pressure and flow deflection behind the reflected shock for the flip to Mach reflection (see Sudani & Hornung 1998).

points observed experimentally. In this situation, two solutions, i.e. regular and Mach reflections, are theoretically possible. For a certain deflection angle (indicated by θ_N) lower than θ_t, the incident shock locus and two reflected shock loci intersect with one another. Obviously, this situation corresponds to the von Neumann condition. For a certain angle (indicated by θ_d) greater than θ_t, on the other hand, reflected shock loci intersect with each other at only one point. If the deflection angle is increased slightly, no intersection would exist, and regular reflection would be physically impossible. This can only be the detachment condition. The dual-solution domain can therefore be achieved using the asymmetric arrangement as well as the conventional symmetric one (for example, in Hornung & Robinson 1982).

Figure 8 shows a sequence of schlieren pictures for model 1 when the upper deflection angle is increased (from *a* to *d*) and reduced back (from *e* to *h*). For the same θ_u (figures 8*b* and 8*g* or figures 8*c* and 8*f*), both regular and Mach reflections appear, and a hysteresis effect is evident. The Mach stem length is plotted in figure 9 against θ_u for different aspect ratio models with g/L nearly constant. The shaded region denotes the range between the von Neumann and detachment conditions determined from figure 7. As the model aspect ratio is increased, the deflection angle at the transition to Mach reflection tends to decrease. The transition back to regular reflection, on the other hand, occurs almost at the same deflection angle for all the models. The Mach stem lengths for models 2 and 3 are nearly the same, while that for model 1 is significantly shorter. This suggests that the model aspect ratio (or inlet aspect ratio) for model 2 is sufficient for achieving a two-dimensional phenomenon. The deflection angles at the transition from Mach to regular reflection should be very close to the von Neumann criterion, but seem to be significantly above the criterion. The difference between these angles and the criterion value would not be eliminated even if the slight bend of the sting were taken into account. A reason for the discrepancy is thought to be the three-dimensionality of the subsonic region behind the Mach stem. Furthermore, since the Mach stem is gradually reduced, the detection of the transition angle from video footage is somewhat subjective. In computations, the transition phenomenon is strongly dependent on the grid size near the reflection

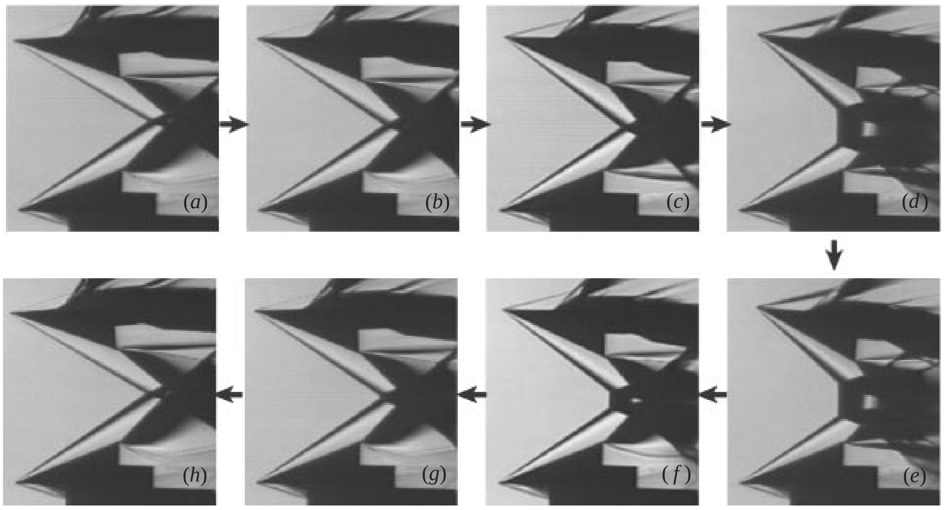

FIGURE 8. A sequence of schlieren pictures at the transition between regular and Mach reflections in the asymmetric arrangement. Model 1, $M_\infty = 4.015$, and $\theta_l = 22.6°$. $\theta_u =$ (*a*) 17.0, (*b*) 20.0, (*c*) 22.8, (*d*) 27.0, (*e*) 27.0, (*f*) 22.8, (*g*) 20.0, and (*h*) 17.0°.

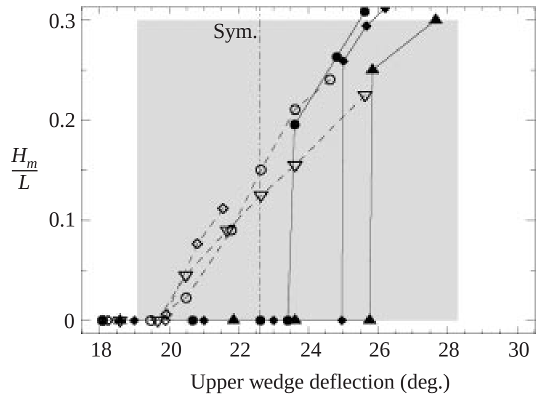

FIGURE 9. Variation of Mach stem length with the deflection angle of the upper wedge. $M_\infty = 4.015$ and $g/L \simeq 0.37$. Triangles, model 1; diamonds, model 2; circles, model 3. Solid symbols, data with increasing θ_u; open symbols, data with decreasing θ_u.

point. To remove these ambiguities, further investigations with finer resolution will be required both experimentally and numerically.

3.3. *Stability of regular reflection*

Another series of tests has been conducted using lower wedges with different deflection angles in the asymmetric arrangement to investigate the repeatability of the transition angle and the stability of regular reflection in the dual-solution domain. Upper deflection angles at the transition from regular to Mach reflection are plotted against lower deflection angles in figure 10. In all cases, the transition to Mach reflection occurs significantly above the von Neumann condition but below the detachment condition, while it occurs slightly above the detachment condition in computations. (The slight differences are thought to be attributable to computational time lag in unsteady calculations. The rate of the wedge movement is not so small as to be

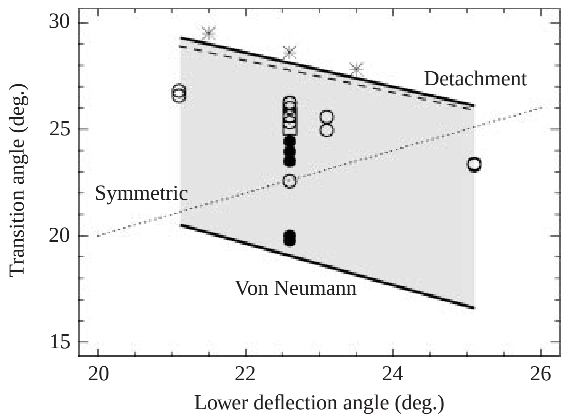

FIGURE 10. Upper deflection angles at the transition from regular to Mach reflection with various lower wedge angles. $M_\infty = 4.015$. ○, model 1; □, model 2; ●, model 3; $*$, computations by Mizobuchi *et al.* (1999).

neglected compared with the flow characteristic time. See Mizobuchi *et al.* 1999 for details.) It is interesting to find that the maximum transition angle for each lower deflection angle is approximately 2.5° lower than the angle for the detachment condition. The dashed line close to the detachment criterion represents the condition in which the flow downstream of the reflected shock becomes subsonic, and analysis suggests that this condition is the actual point of the transition to Mach reflection. Moreover, the deflection angle due to the bend of the sting supporting the upper wedge is estimated to be not more than 0.2°. Although the transition to Mach reflection occurs significantly below the detachment criterion, it can be inferred that the transition criterion obtained experimentally has some relation to the detachment criterion derived from the two-dimensional analysis. The difference between the detachment condition and the maximum transition angles (2.5°) is presumably related to the magnitude of perturbations of free-stream properties.

In contrast to these results, the experiments of Li *et al.* (1999) at a Mach number of 5 show that the transition from regular to Mach reflection is observed very close to the theoretical detachment angle. The pair of wedges used in their experiments, however, had an inlet aspect ratio of around 1. It is probable that such a low aspect ratio promotes regular reflection as mentioned in § 3.1 and that the transition angles in the experiments by Li *et al.* (1999) are greater than those in our experiments. The effects of inlet aspect ratio on upper deflection angle at the transition to Mach reflection and the repeatability of the transition angle are shown in figure 11. The scattered experimental data were acquired in separate runs. Computations by Mizobuchi *et al.* (1999) at a Mach number of 4 indicate that three-dimensional effects increase dramatically around an inlet aspect ratio of 1. They also suggest that an aspect ratio of at least 1.5 would be required to achieve a two-dimensional phenomenon for this Mach number. It can be seen that our experimental setup satisfies the condition for all cases. However, as the inlet aspect ratio is increased, the maximum transition angle decreases, and the repeatability appears to deteriorate slightly.

The results of all these experiments lead to the hypothesis that the predominant cause of the transition from regular to Mach reflection are some disturbances existing in wind tunnel flows. The following facts derived from the experiments support the hypothesis:

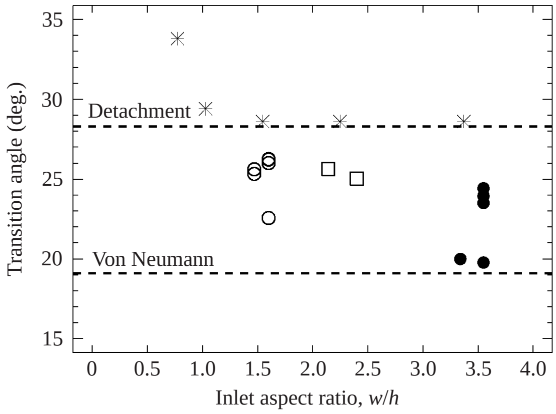

FIGURE 11. Effects of inlet aspect ratio on upper deflection angle at the transition from regular to Mach reflection. $M_\infty = 4.015$ and $\theta_l = 22.6°$. Symbols as in figure 10.

(i) In the symmetric arrangement discussed in § 3.1, the transition to Mach reflection occurred irrespective of the direction of the upper wedge movement. In ideal flow, subsonic flow cannot be produced in the vicinity of regular-reflection points, so that a Mach stem should never appear.

(ii) Some observations recorded that the transition to Mach reflection happened incidentally while there was no change in the position and deflection angle of either wedge during a run.

(iii) The repeatability of the transition point could not be achieved satisfactorily. If a certain specific factor dominated the transition, the repeatability would be better because the transition would occur at a particular wedge configuration. It is therefore possible that the transition is promoted by an unknown factor.

If disturbances existing in the free stream caused the transition, this would provide a convincing explanation for figures 10 and 11. Sudani & Hornung (1998) provided a physical argument for the stability of regular reflection to disturbances behind the reflection point. Recently, in more quantitative terms, Khotyanovsky, Kudryavtsev & Ivanov (1999) estimated the magnitude of disturbances causing the transition by adding density perturbations to the free stream. Both showed that regular reflection became less stable as it approached the detachment condition. When the upper deflection angle is increased from the von Neumann condition, the regular reflection can permit a disturbance (a kind of perturbation of free-stream properties) if the disturbance level is sufficiently low. The transition will happen before the arrival at the detachment condition, however, when the permissible level decreases below the flow disturbance level. As mentioned in § 2.1, the results of pressure fluctuation measured in the present wind tunnel (Hashidate *et al.* 1982) demonstrated the same trend in any period during a run and good repeatability from run to run. One could expect that the regular reflection would always persist until near the maximum transition angle mentioned above if another type of disturbance were not present. However, some observations that the transition (to Mach reflection) occurs significantly below the maximum transition angle imply the existence of an irregular disturbance. This causes irregular phenomena such as (i) and (ii) and leads to the poor repeatability of the transition point as shown figures 4, 10, and 11. If the disturbance were also spatially non-uniform, a higher aspect ratio model (when g is constant) might be expected to be geometrically more susceptible to the effects of disturbances, as shown in figure 11. Even if a section of the regular reflection points were disturbed and Mach reflection occurred locally, the effects would spread instantly in the spanwise direction. This accounts for the experimental observation that the scatter in transition angle tends to become greater with the increase in inlet aspect ratio.

The traces of Mach number and static pressure during a run (for example, as shown in figure 4*c*) indicated no perturbation with a very low frequency and no sudden turbulence. To clarify what kind of disturbance is most dominant, the stability of regular reflection has been investigated by producing some disturbance artificially. In the present studies, we have tried to change the settling chamber pressure by approximately 4% during the run and to inject a different gas (helium) or water in the settling chamber. In the next section, the case of the water injection is discussed because it gave the most significant results.

3.4. *Effects of disturbances*

In a series of tests with the vapour-screen visualization, the transition to Mach reflection tended to occur near the von Neumann condition. Water vapour has been identified as a disturbance causing the transition, and thus the influence of water vapour has been investigated to study disturbance effects on the transition phenomenon. Figure 12 shows the point of the transition from regular (RR) to Mach reflection (MR) for two asymmetric cases in which water is injected in the same way as the vapour-screen visualization. Both wedge deflection angles are fixed during a run, and, if the bend of the sting is taken into account, the upper deflection angle is estimated at approximately 0.2° above the von Neumann condition. It was confirmed, in another run, that no transition happened in this wedge arrangement without the water injection. A solenoid valve for injecting water is opened 20 s (the first dotted line) after the tunnel operation starts, but it takes some time for water to arrive at the settling chamber from the container. The actual time of the water arrival can be derived from the trace of free-stream static pressure or Mach number. The transition indicated by a solid line occurs at the same time when the static pressure or Mach number starts to change (at 23.1 s for case *a* and at 21.4 s for case *b*). The slight drop in Mach number caused by injecting water reduces the deflection angle at the von Neumann condition by approximately 0.02°. This value is, however, considered insignificant with respect to the difference between the upper deflection angle tested and that at the von Neumann condition (the value of 0.2°). Even a very small amount of water vapour producing an insignificant change in Mach number can cause the flip to Mach reflection.

The transition from regular to Mach reflection and vice versa is observed by changing the upper wedge angle continuously when water is injected immediately after the free stream is established. A sequence of schlieren pictures is shown in figure 13. Traces of free-stream static pressure and Mach number indicate that water is injected uniformly as the upper wedge changes its deflection angle. Nevertheless, the transition from regular to Mach reflection happens near the von Neumann condition, and no clear hysteresis effect is recognized. (The reflections in figures 13*b* and 13*g* are considered Mach reflections because two slip lines can be observed behind the reflection points.) Without the water injection, on the other hand, a clear hysteresis has already been confirmed in the same arrangement (Sudani *et al.* 1999*b*). It is experimentally proved that the hysteresis phenomenon cannot occur in a perturbed flow.

However, the mechanism of the transition by water vapour produced artificially as a disturbance has not yet been properly understood. The analysis shows that

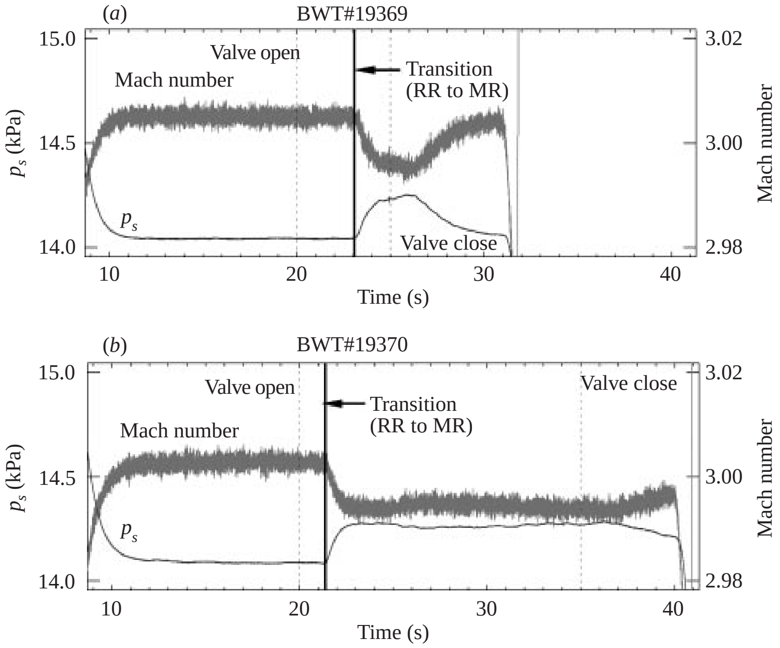

FIGURE 12. Time histories of the free-stream static pressure p_s and Mach number with water injected. Model 4, $\theta_u = 19.2°$, and $\theta_l = 20.2°$. Transition from regular to Mach reflection occurs at 23.06 s in case (*a*), and at 21.37 s in case (*b*).

the slight changes in free-stream Mach number and static pressure induced by the water injection should be insignificant for the transition (the deliberate change in the chamber pressure by 4% during a run did not produce the transition). Even if all water droplets evaporated downstream of the reflected shock, effects of the change in temperature on velocity would be negligible because the heat of evaporation is only 0.4% of the kinetic energy per mass of air. Although the water injected has no significant effects on flow characteristics, it can surely be a disturbance which induces the transition to Mach reflection. The transition may be caused by non-uniform distributions of flow characteristics (Mach number, static pressure, etc.) in the test section because of condensation of water in the nozzle. If this were the main reason, however, it would be very difficult to account for the fact that the transition occurs even without deliberate disturbances because sufficiently dry air was used to run the tunnel. Another possibility is that water droplets themselves produce an effective subsonic region in the vicinity of the regular reflection point. If this were the case, unavoidable tiny particles which exist to a greater or lesser degree in the free stream might cause the transition when they pass near the reflection point accidentally, and this could lead to the irregular phenomenon. Actually, it was sometimes observed that dust particles (not larger than 0.1 mm) impinged on the wedge surface or the leading edge, and these are thought to be larger than water droplets. This is considered to be not unusual in blow-down wind tunnels unless special care is taken in the settling chamber or at the nozzle entrance, and the effects can be usually neglected for conventional measurements of forces or pressure. It is open to question, however, whether regular reflection is so unstable as to be easily collapsed by such small particles. The present studies suggest that irregular behaviours of the transition to Mach reflection might be observed in other conventional wind tunnels because,

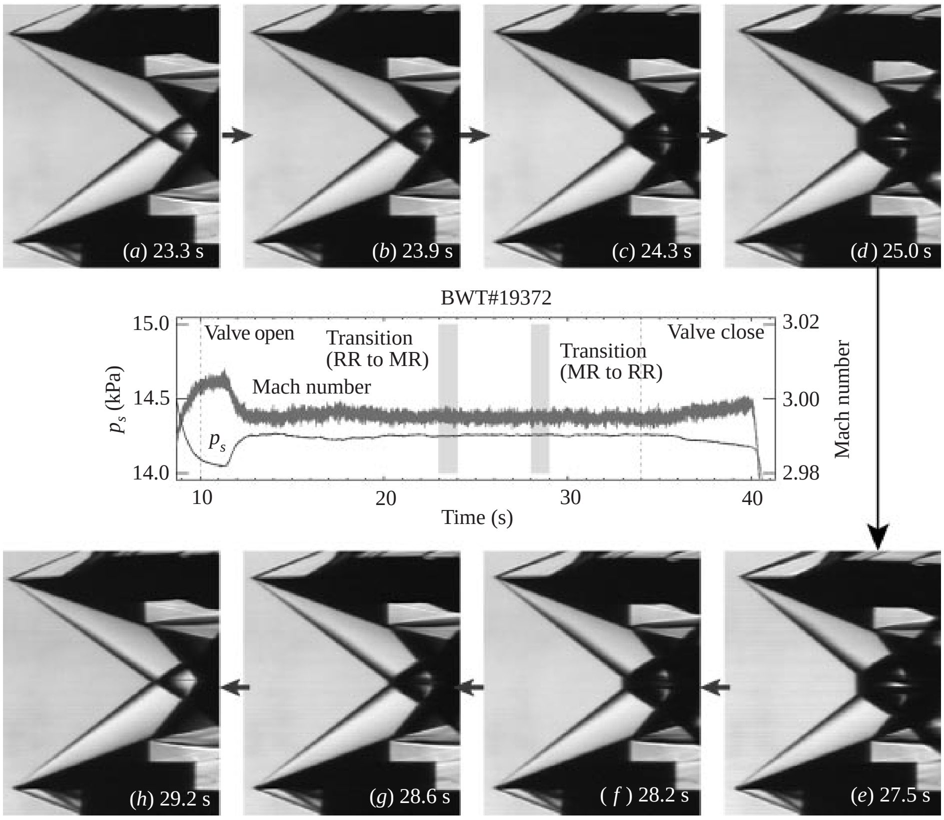

FIGURE 13. Transition from regular to Mach reflection and vice versa with water injected in the asymmetric arrangement. No clear hysteresis effect is observed. Model 4, $\theta_l = 20.2°$. $\theta_u =$ (*a*) 17.8, (*b*) 19.0, (*c*) 19.8, (*d*) 21.2, (*e*) 21.2, (*f*) 19.8, (*g*) 19.0, and (*h*) 17.8°.

undesirably, a small irregular disturbance is more effective for the collapse of regular reflection. One can also expect that the transition to Mach reflection would occur near the von Neumann condition if the air used in the free stream were not so dry as to prevent the condensation of water vapour completely. The results in the present studies suggest careful data interpretation for future experiments in conventional wind tunnels.

According to Sudani & Hornung's (1998) discussion, if the flow condition downstream of the regular reflection point changed by $\Delta\theta$ or Δp (see figure 7), regular reflection could flip to Mach reflection. In Khotyanovsky *et al.*'s (1999) numerical studies, density perturbations of more than 30% of the free stream value are necessary for the transition to Mach reflection near the von Neumann condition. It is reasonable to expect, however, that the Mach number and pressure fluctuation of the free stream in the wind tunnel used in the present experiments never cause perturbations exceeding such a high tolerance level. It is possible that regular reflection is much less stable than predicted by the analyses or that an unexpected irregular disturbance is dominant in wind tunnel experiments. To verify our conclusion or to clear up the uncertainties, experiments in a quiet (low-turbulence) and clean (dust-free) wind tunnel are needed. The transition to Mach reflection would occur very close to the detachment condition in such a situation. Comparing data from various wind tunnels with known disturbance levels is also recommended.

4. Conclusions

Experimental studies of shock wave reflections in steady flows have been conducted at Mach numbers of 3, 3.5 and 4 in a blow-down supersonic wind tunnel.

In a symmetric arrangement, in which the upper wedge is moved vertically with its deflection angle fixed, both regular and Mach reflections are experimentally proved to be possible in the dual-solution domain. In some cases, the transition to Mach reflection does not occur until the flow between the wedges chokes. It is also possible that the transition occurs at any location irrespective of the direction of the inlet aspect ratio variation. The increase or decrease in inlet aspect ratio, i.e. the three-dimensionality of experimental models, cannot be a cause of the transition provided the inlet aspect ratio is high enough for the regular reflection point at the spanwise centre to be free from the information from wedge edges. Application of the vapour-screen visualization technique shows that the Mach stem has its maximum length at the spanwise centre, and that, in a region influenced by the edge information, the three-dimensionality of experimental models promotes regular reflection rather than Mach reflection.

In an asymmetric arrangement, in which the upper wedge changes its deflection angle continuously, a hysteresis effect is evident. The transition from regular to Mach reflection occurs significantly above the von Neumann condition but below the detachment condition as the upper deflection angle increases, while the Mach reflection persists until near the von Neumann condition in the opposite direction. The repeatability of the transition angle, however, is not satisfactorily achieved and deteriorates slightly as the inlet aspect ratio is increased. However, this irregular phenomenon is probably not due to fluctuations of free-stream properties (static pressure, etc.), and supports the hypothesis that an irregular disturbance existing in the free stream of wind tunnels dominates the transition to Mach reflection in the dual-solution domain. It is suggested that such an irregular phenomenon can happen undesirably in conventional wind tunnel experiments. These facts are expected to provide useful information for future experiments on Mach reflection.

For various lower deflection angles, the difference between the detachment condition and the maximum angle at the transition to Mach reflection for each lower deflection angle is almost constant. This implies that the transition phenomena observed experimentally have some relation to the detachment criterion derived from the two-dimensional analysis and that the differences occur because of the uniform perturbation inherent in the free stream. The regular reflection becomes less stable with the increase in deflection angle, and the transition happens when the disturbance level exceeds the tolerance level of the regular reflection.

The effects of disturbances were then investigated by producing water vapour deliberately in the free stream in the same manner as for the vapour-screen method. The transition occurs without fail when a very small amount of water vapour reaches the test section, and no clear hysteresis effect is observed in the flow with water vapour included. The mechanism of the transition by water vapour, however, remains uncertain, and the question arises as to what kind of disturbance causes irregular behaviour of the transition in wind tunnel experiments without deliberate disturbances. Experiments in a quiet (low-turbulence) and clean (dust-free) wind tunnel will be needed to clarify the effects of wind tunnel disturbances.

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